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DTRC-SME-90/28 Method for Evaluating the High Strain-Rate Compressive Properties of Thick Composite Laminates

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Method for Evaluating the High Strain-Rate Compressive Properties of Thick Composite Laminates

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A test apparatus and methodology developed to obtain high strain-rate compressive mechanical properties of various fiber-reinforced composite materials is described. This direct compression method utilized a drop tower to impart a load at dynamic rates to the test fixture. Uniform specimen loading was accomplished through the use of aligned guide rails to constrain all but the vertical motion of a free-sliding impactor. Specimen endcaps, specific to thick-section testing, were implemented to prevent premature brooming failure. A piezoelectric transducer and aluminum absorbers were some of the refinements introduced to alloy acquisition of stress and strain data free of distortion. Strain rates on the order of 8 sec^{-1} have been achieved, and higher rates appear possible. Material property data was obtained on a series of AS4 graphite/PEEK thermoplastic $0_2 90$ composite laminates. The results of the first study indicated that at high strain rate loading, the strength of this material increased 42 percent over static values and the strain to failure increased by 25 percent, whereas the elastic modulus remained unaffected.

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ABSTRACT

A test apparatus and methodology developed to obtain high strain-rate compressive mechanical properties of various fiber-reinforced composite materials is described. This direct compression method utilizes a drop tower to impart a load at dynamic rates to the test fixture. Uniform specimen loading was accomplished through the use of aligned guide rails to constrain all but the vertical motion of a free sliding impactor. Specimen endcaps, specific to thick section testing, were implemented to prevent premature brooming failure. A piezoelectric transducer and aluminum absorbers were some of the refinements introduced to allow acquisition of stress and strain data free of distortion. Strain rates on the order of 8 sec^{-1} have been achieved, and higher rates appear possible. Material property data was obtained on a series of AS4 graphite/PEEK thermoplastic $0_2 90$ composite laminates. The results of this first study indicated that at high strain-rate loading, the strength of this material increased 42 percent over static values and the strain to failure increased by 25 percent, whereas the elastic modulus remained unaffected.

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INTRODUCTION

Fiber-reinforced nonmetallic composites have shown great promise as high strength structural materials for naval applications, due to the potential benefits of decreased weight and increased stiffness. However, the future of advanced composite systems for most naval structures depends on an in-depth understanding of how these materials behave under high-rate loading conditions. There currently exists only a limited body of knowledge of the properties and failure behavior of these materials at high strain-rates to support dependable design for naval applications. One such case is modelling the response of composite cylinders to shock loading. Analytical methods have been used to simulate the structural response of a composite cylinder during a dynamic shock event. However, for these models to be accurate, realistic high strain-rate material property input is needed in the analysis. Quasi-static data may not be adequate for design analysis, since it has been shown that modulus, strength, strain-to-failure and failure modes of composites can vary significantly with strain rate [1,2]. Unfortunately, the high strain-rate behavior of the thick section composites utilized in this application is a relatively unexplored area. Dynamic testing of these materials by any loading mode has been very limited, and the results found in the available literature are inconsistent due to limited test techniques and specialized specimen geometries. This lack of accurate high strain-rate material property data for thick section composites has impeded the utilization of these materials in the Navy. The work described in this report was initiated to develop the experimental techniques required to assess the high strain-rate compressive properties of thick section composite material systems. Specifically, a test methodology for high strain-rate compression testing of end-loaded thick section composite laminate coupons has been developed.

The quantitative definition of strain-rate ranges is generally arbitrary, since the range is usually defined by the material response. In using the term "high strain rate" we have followed the guidance of Rotem and Lifshitz[3], who categorized the high strain-rate regime for composites as being in the range of 5 - 30 sec^{-1}.

EXPERIMENTAL PROCEDURE

Test Method and Supporting Apparatus

Earlier in-house investigations indicated that the compression test fixtures used for quasi-static testing of thick section laminates could not be readily adapted for testing under a dynamic loading. The first phase of this work, then, was to design a new compression apparatus to dynamically impact an end-loaded coupon, where load was introduced by direct bearing on the end of a short, rectangular specimen of appreciable thickness (greater than 2.54mm thick) and unsupported gage length. The new apparatus is pictured in Figure 1. The fixture consisted of a tee-shaped impactor that was aligned and directed by two vertical guide rails, one on each side. The rails were bolted into a channel contained in a steel base perpendicular to the rails, which aligned the rails both perpendicularly to the base and laterally with one another. The lateral distance of separation between the rails was adjustable to accomodate free sliding of the impactor. The impactor was machined from AISI 4340 steel, hardened to 44 HRC. A hardened 4340 steel bottom plate was seated between the rails to provide a flat surface, parallel to the impactor bottom face, on which to place the specimen. Close tolerances were specified for flatness and perpendicularity on the contact faces to minimize specimen out-of-plane loading.

A drop tower assembly was used to achieve a loading duration within an order of magnitude of that achieved during the explosion tear test, which has been designed to be characteristic of the loading response of a metallic structure to dynamic loading[4]. The free-falling crosshead of the drop tower, guided by the drop tower load frame, was used to impart load to the test fixture. The test fixture is shown installed in the drop tower in Figure 2. The falling drop tower crosshead tup directly contacted the top of the fixture impactor; a vertical stud on top of the impactor was threaded to accomodate a piezoelectric load cell, which transmitted the load signal. A small, pyramidal absorber made of 6061-O aluminum (fully annealed condition) was positioned between the load cell and the drop tower tup. The function of this absorber was to damp out the spurious noise in the load and strain histories due to apparatus vibrations and steel-on-steel contact, where the deformation of the pyramid shape served to smoothly and evenly transfer the load to the tee-shaped impactor. This technique has been employed by Joyce and Hackett[5] using different absorber configurations. The crosshead was dropped from 0.305 meters (2 feet) and was arrested by rigid stops after the specimen was impacted and displaced to failure. Strain data was obtained from strain gages mounted directly on the specimen. The data from the load cell and the specimen strain data were recorded on a Nicolet 4094 series digital oscilloscope, then transferred to a personal computer for data reduction and analysis. The strain rate was derived from the strain-time curve. The tup velocity at impact was recorded using an optical flag system.

Specimen Design

The specimen used in this study was modelled after the thick section test coupon used at NASA-Langley for static compression testing[6]. The specimen size was nominally 6.4 mm (0.25 in.) thick by 31.8 mm (1.25 in.) in width. The specimen length was 44.4 mm (1.75 in.), which included a 25.4 mm (1.0 in.) unsupported gage section and 9.5 mm (0.375 in.) grip lengths on either end. These dimensions were considered appropriate for the initial material study; however, the fixture can accomodate specimens through a wide range of sizes. Specimen ends were ground flat and parallel to within 0.0254 mm (0.001 in.) to ensure uniform load distribution to the specimen cross-section.

Specimen endcaps were employed to suppress the end-initiated brooming failure which often occurs in end-loaded specimens with large percentages of fibers oriented in the load (0°) direction. Prevention of brooming in coupon specimens allows more direct relation between coupon data and cylindrical specimen data, since the modelled 'zero direction' of a cylinder is circumferential and, therefore, is not susceptible to end initiated failure. The specimen was gripped using the reusable, rectangular endcaps, as illustrated in Figure 3. The specimen ends were recessed into the hardened steel endcaps to a depth of 9.5 mm (0.375 in.), then adhesively bonded using a room temperature curing epoxy adhesive to provide end restraint. A similar endcap concept has been used successfully with cylindrical metal matrix composite specimens by Lamothe and Nunes[7], and with glass/polyester specimens by Han[8]. The specimen endcaps were separable from the fixture itself, and could be utilized in static testing as well. The endcaps each consist of two pieces, a containment piece and a contact surface (see figure 3). The first purpose of this design was accurate specimen alignment. The specimen was first bonded into the containment piece with the epoxy adhesive. During the epoxy curing cycle the specimen end is held against the flat contact surface. After curing, the containment piece and contact surface can be unbolted, allowing visual examination of the specimen end to ensure that it is flush and parallel to the endcap. The other advantage of this design was ease of specimen removal. After testing, the contact surface could be removed from the endcap, facilitating removal of the specimen for postfailure examination without incurring further damage.

The specimens were instrumented with longitudinal strain gages to measure longitudinal strain and to detect any out-of-plane deflection that would occur from global specimen instabilities. A 6.35 mm (0.25 in.) longitudinal gage was applied in the center of the gage length on each side of the specimen. The strain gages were applied with M-bond AE-10 adhesive to prevent premature debonding.

Material

The material investigated in this initial study was an AS-4 graphite/APC-2 Poly-Ether-Ether-Ketone (PEEK) thermoplastic composite. Carbon reinforced PEEK is a high performance composite that is potentially advantageous for naval applications compared to carbon/epoxy systems. The toughness of the matrix material provides good impact resistance, and its flammability, toxicity and smoke density characteristics are superior to those of epoxy systems.

The material was supplied as a hot-press molded plate by Fiberite Corporation. The plate was fabricated from unidirectional tape pre-impregnated with epoxy, and supplied as a 48 ply (6.4 mm thickness) continuous fiber reinforced laminate of $[0/0/90]_{8s}$ orientation. Fiber volume fraction was calculated to be 61 percent from a resin content of 32 percent by weight. Void content was specified by the manufacturer to be less than 1 percent. An ultrasonic C-scan inspection was performed which indicated no defects.

RESULTS AND DISCUSSION

Mechanical Property Data

After completing initial proof-of-concept tests under both static and dynamic loading, a series of five specimen tests were conducted on the AS-4/PEEK specimens for both the static and high strain rate conditions. The data for the static tests is given in Table 1. The static test results were obtained using the same endcap grips, to allow direct comparison of the static data with the dynamic test results. Static tests run on a similar material (an AS-4 graphite/3501-6 epoxy resin composite) using these grips compared well with static results obtained for the same material using another thick section, end-loaded grip method[9]. The average static compressive strength of this material was 798 MPa (116 Ksi), the average initial modulus was 82.7 GPa (12.0 million psi) and the average strain to failure was 1.03 percent. A typical stress-strain curve for these tests is shown as Figure 4.

High strain-rate test results obtained with the proposed fixture are shown in Table 2. The mean strain rate attained in these tests was 7.9 sec^{-1}. The average dynamic compressive strength for the AS-4/PEEK material at this rate was measured to be 1141 MPa (165 Ksi). This represents a forty-three percent increase over its measured static strength. The average measured dynamic ultimate strain of 1.30 percent for this material was also higher than the static measured value, and represents a twenty-six percent increase. The high strain rate elastic modulus averaged 81.4 GPa (11.8 million psi) and was nominally reproducible for these specimens. Since the elastic moduli measured at static and dynamic rates were equivalent, there appeared to be no effect of increased strain rate of this magnitude on the elastic modulus of this material. The curves in Figure 5 show typical load cell and strain gage responses for the dynamic tests of specimens. It should be noted that the strain traces from the opposed gages were comparable, indicating negligible bending, and that peak strains and peak load occured simultaneously. Figure 6 illustrates the degree of alignment achieved during testing as a stress-strain plot: The two signals plotted were from back-to-back vertical strain gages mounted oppositely on a representative specimen. The lack of bending indicated a high degree of alignment among the drop tower tup, fixture, and specimen. No significant bending was observed in any of the dynamic tests.

The stress-strain traces for three dynamic tests are shown in Figure 7 with two traces from static tests plotted for comparison, illustrating the equivalence of the static and dynamic elastic moduli, but showing higher peak properties of the dynamic tests.

Failure Mode

Different mechanisms often govern the deformation behavior of materials within different strain-rate regimes[10]. For this reason, the static and dynamic specimens were examined and compared for differences in failure behavior. The failure modes of the AS-4/PEEK specimens tested at static and high strain rate in this study were similar, although greater damage was incurred in the high strain rate specimens. This was due in part to the continued travel of the impactor after specimen failure initiation which propagated damage. The drop tower crosshead was stopped as soon as possible after coupon failure to avoid crushing the specimen; however, the estimated allowed travel distance was necessarily larger than that required for the specimen ultimate strain to failure. Photographs of typical failed static and dynamic specimens are shown in Figure 8. Both static and dynamic specimen failures exhibited a regular delamination pattern as well as a crush zone. The delaminations occurred every three plies at one side of the 0-90 degree interface as pictured in Figure 9. Crush zones were present close to the endcaps at one or both ends; kink band and shear crippling failures can be observed in these regions, for both static and dynamic specimens, as shown in Figure 10.

SUMMARY

A test apparatus and methodology were developed for the determination of the compressive properties of thick section composite materials at high strain rate. From a limited scope test series, it was found that reproducible strength and failure data were obtained using the described dynamic compression test method. The use of the endcap grips developed for the test method successfully prevented end-initiated brooming failure. Although 'true' compression material property data for composites have been shown to be

dependent on the test method and specimen geometry, the static data obtained via this test method was comparable to that obtained by other thick section test methods. Static and dynamic compression tests of 0_290 AS-4/PEEK using this apparatus and methodology demonstrated that the elastic compressive modulus of the material was not strain rate sensitive, while both ultimate strength and strain to failure were increased at high strain rate.

Because the fixture can be used for determining compressive strength properties for varied specimen sizes over a significant range of thickness and lengths, this method may be useful as a comparative measure of high strain rate compressive properties for a variety of fiber-reinforced composite materials and laminate layups. Other dynamic methods, by contrast, are limited by inherent constraints in specimen size. Additionally, since the end constraint and specimen geometry for these high strain rate tests are the same as those employed in the static tests, this method can be utilized to directly compare the static and dynamic reponses of a given material, allowing assessment of the effects of strain rate on that laminate system. Because of these capabilities, this high strain rate test method can provide a more realistic assessment of composite structural response to dynamic loads than other dynamic test methods.

Table I. Static Compression Test Data for AS-4/PEEK Material (0_290 orientation)

SPECIMEN I.D.	AREA (mm)	UCS (Mpa)	MAX (micr [V1]	STRAINS ostrain) [V2]	ELASTIC MODULUS (Gpa)
AC-1	201.6	841	11490	10900	82.7
AC-2	199.1	883	11800	11000	81.4
AC-3	198.7	717	9500	9400	80.7
AC-4	196.6	758	9794	10070	84.1
AC-6	200.5	793	9200	10100	84.8
AVERAGES:	199.3	798.4		10,325	82.7

Table II. High Strain Rate Test Data for AS-4/PEEK Material (0_290 orientation)

SPECIMEN I.D.	AREA (mm)	UCS (Mpa)	MAX (micro [V1]	STRAINS strain) [V2]	ELASTIC MODULUS (Gpa)	STRAIN RATE (sec)
AC-7	198.7	1200	13044	12150	12.0	7.4
AC-8	195.6	1145	12817	12938		7.8
AC-9	196.5	1103	13968		11.2	8.1
AC-10	194.2	1117	12999	10878	12.5	7.8
AC-11	195.9	1138	14120	14029	11.5	8.2
AVERAGES:	196.2	1141	12,994		81.4	7.9

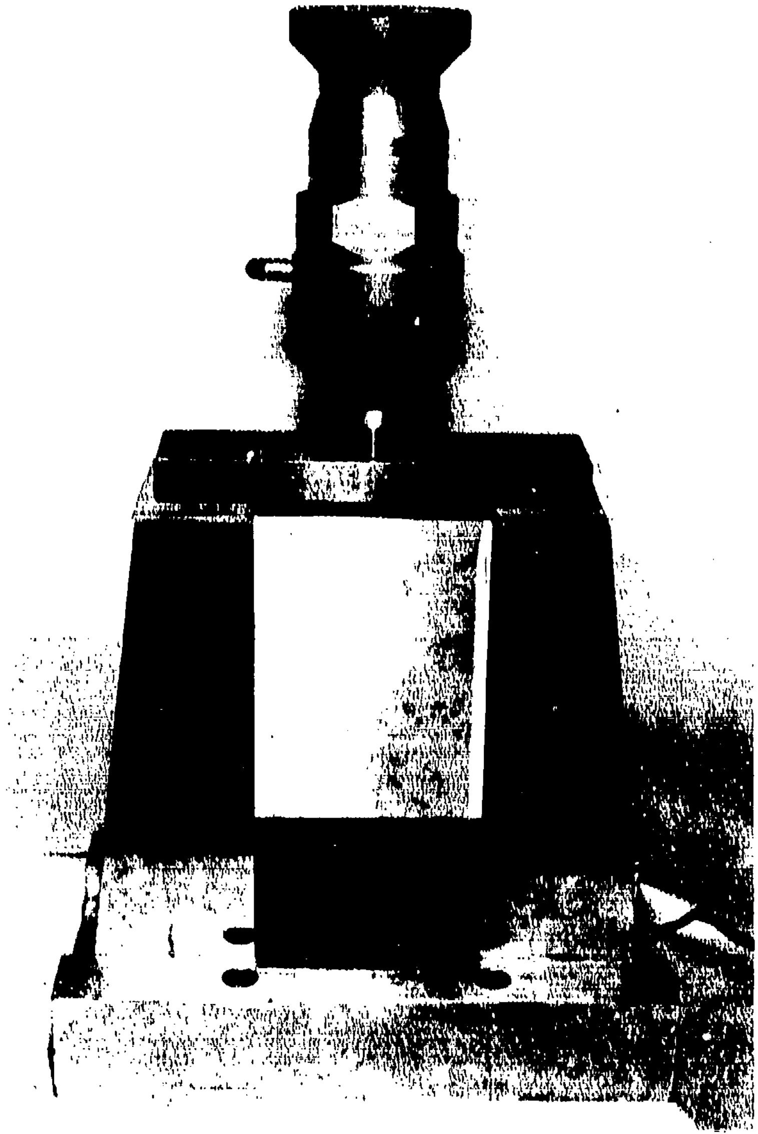


Figure 1. High strain rate compression test fixture.

Figure 2. Photograph of compression test fixture, as installed in the drop tower assembly.

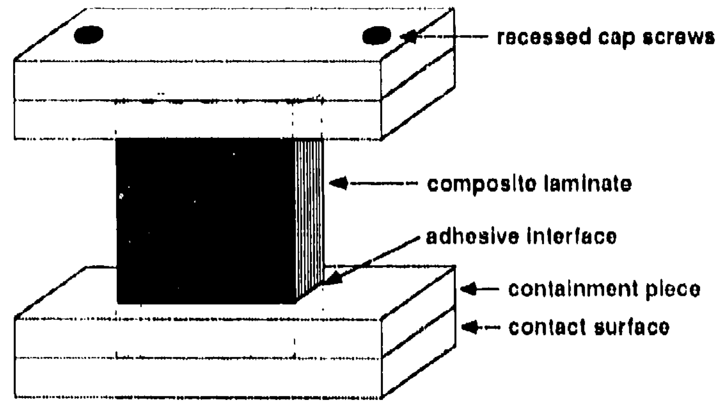


Figure 3. Schematic of specimen geometry and endcap design.

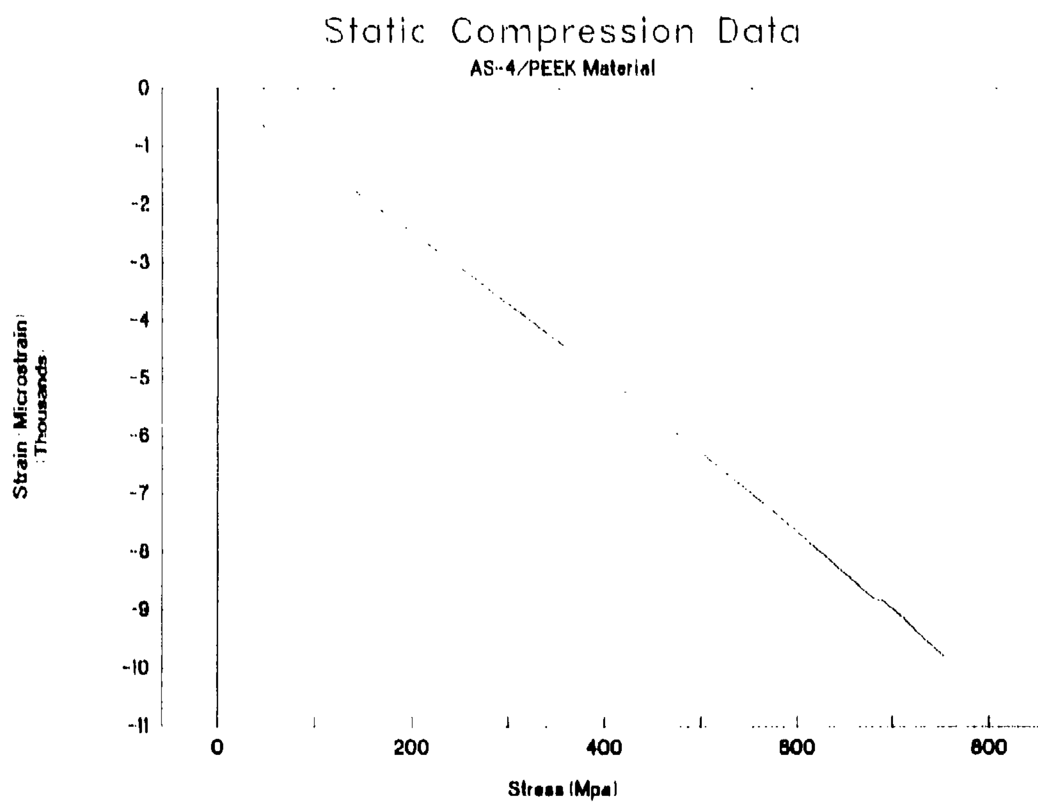


Figure 4. Typical static compression stress-strain curve for AS-4/PEEK material.

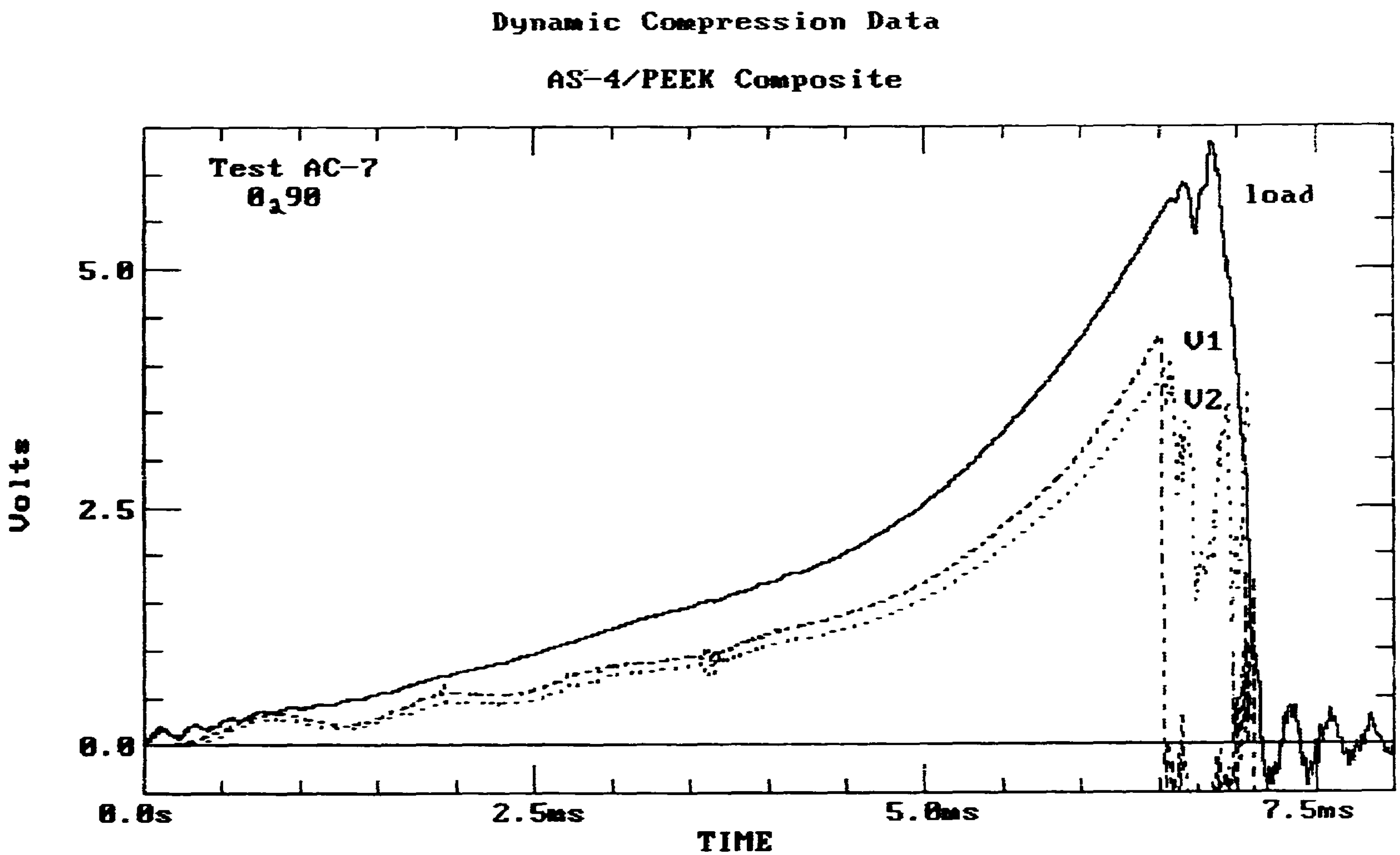


Figure 5. Load and strain histories for an AS-4/PEEK specimen of $0_2 90$ orientation, tested dynamically in compression.

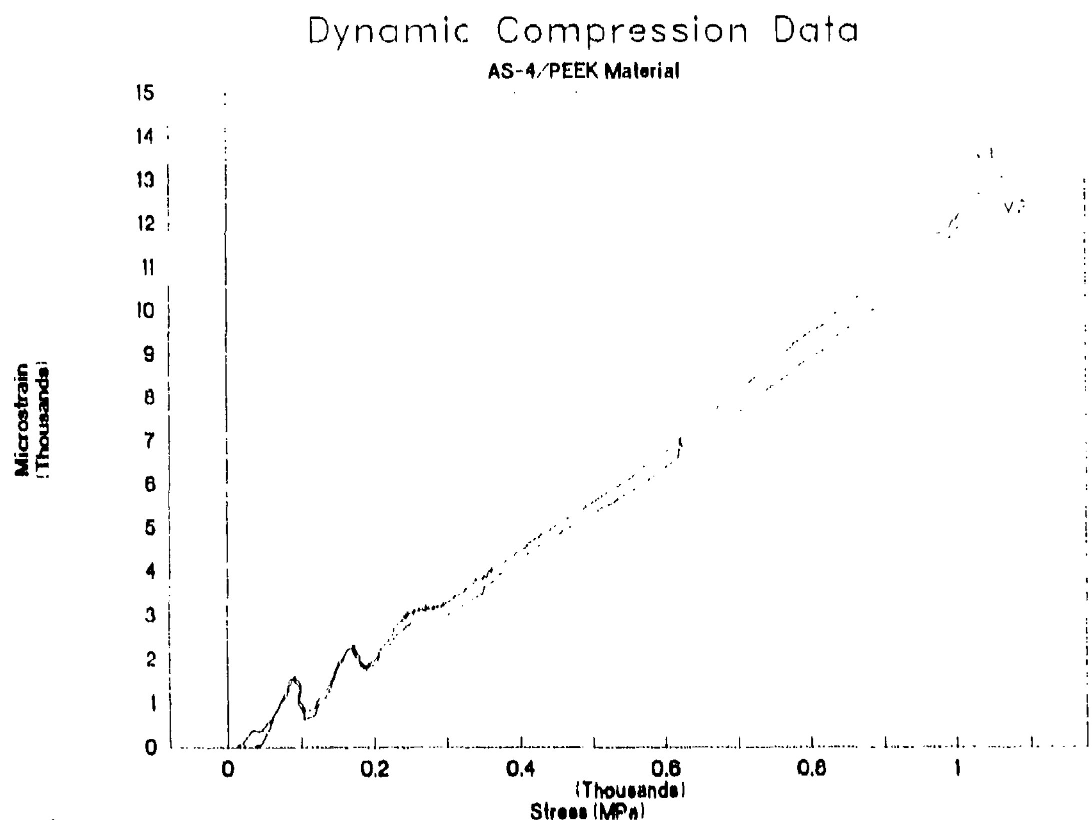


Figure 6. Back-to-back longitudinal strain gage signals for an AS-4/PEEK specimen of 0_290 orientation, tested dynamically in compression.

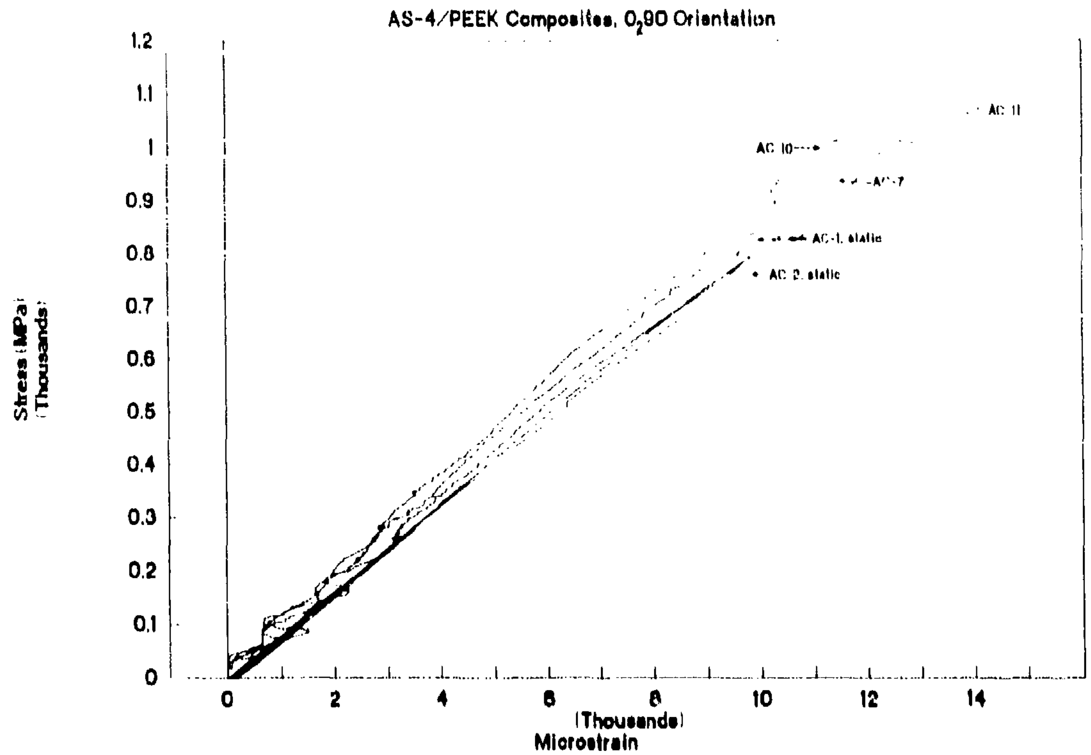
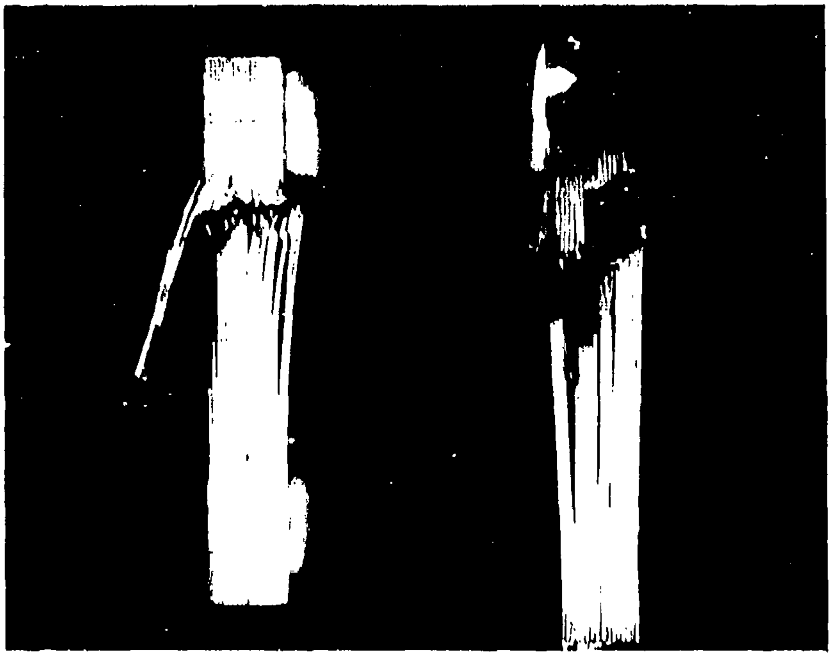
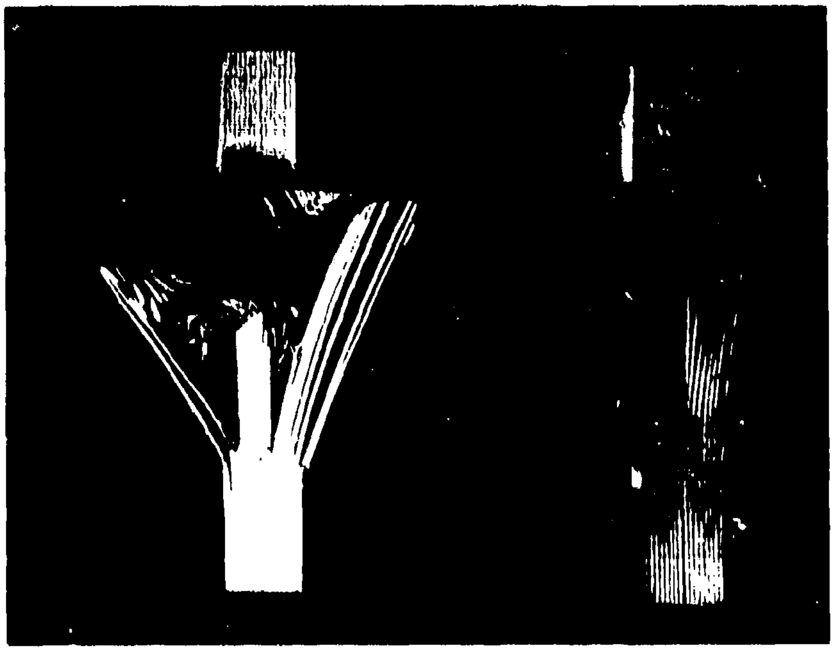


Figure 7. Static and dynamic compression stress-strain plots for AS-4/PEEK material of 0_290 orientation.



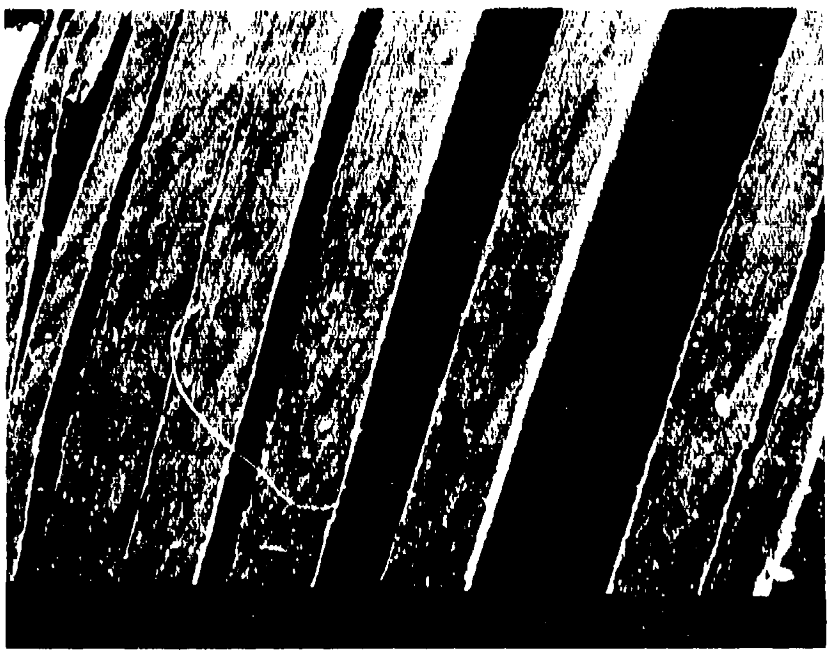
STATIC



DYNAMIC

Figure 8. Photographs of failed static and dynamic specimens.

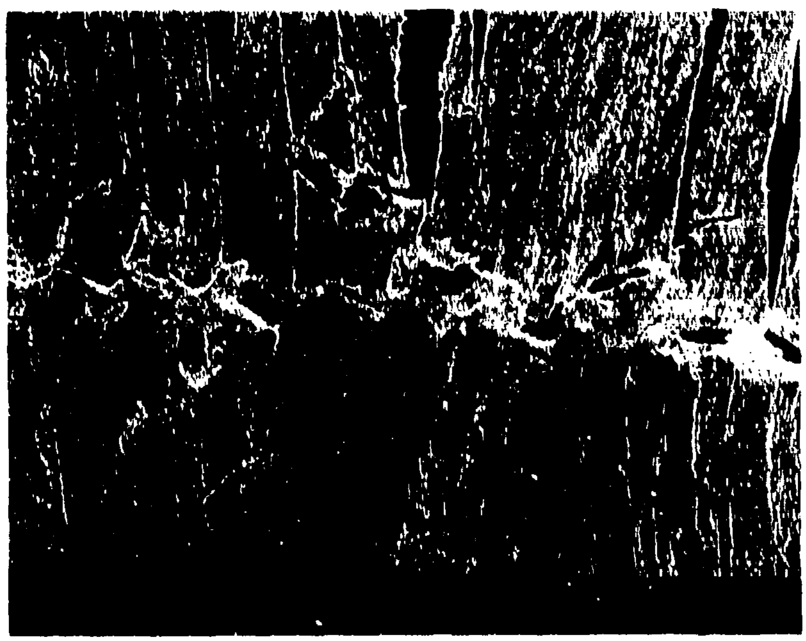
a. AC-2, static test



b. AC-8, dynamic test

Figure 9. Micrographs showing delamination patterns of outer plies in static and dynamic compression specimens.

a. Static specimen crush zone (AC-2) 20



b. Dynamic specimen crush zone (AC-8) 22X

Figure 10. Micrographs of crush zone regions in static and dynamic compression specimens.

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